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Summary report for PSO-F&U project (FU3101)

Fundamentals for remote condition monitoring of offshore wind turbines

Fjernovervågning af Vindmøllevingers Tilstand (fase II)

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Risø-R-1639(EN)

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Abstract (max. 2000 char.):

In the future, large wind turbines will be placed offshore in considerable numbers. Since access will be difficult and costly, it is preferable to use monitoring systems to reduce the reliance on manual inspection. The motivation for the effort reported here is to create the fundamental basis necessary for the use of sensors as a structural health monitoring system for wind turbine blades. This includes creating knowledge that will allow sensor signals to be used for remotely identifying the presence and position of any damage, the damage type and severity, and a structural condition assessment of the wind turbine blades that can integrate with existing SCADA tools to improve management of large offshore wind farms, and optimise the manual inspection/maintenance effort.

Various sensor types, which have previously been identified as technically (and economically) capable of detecting the early development of significant damage in fibre reinforced composite, are investigated. In each case specific approaches have been proposed, developed and implemented in models or laboratory test specimens. The sensor approaches are based on acoustic emission (various passive and active applications including mobile sensors), fibre optics (including a new microbend transducer design and various Bragg-grating based applications), wireless approaches involving both battery and energy harvesting options, and inertia sensor based system identification approaches able to deal with linear periodic systems.

In addition to the sensor investigations, a life-estimate approach for the wind turbines is described based on identifying and characterising critical material failure modes then integrating detailed models of damage progression rates into full scale models of the blade structure under operating loading regimes.

The application of sensors is addressed during a full-scale blade test and recommendations are made regarding improvement to the commercial blade certification process of test and inspection, sensor use for monitoring in-service structural response, and the need for dedicated research facilities providing multi-scale and multi-functional testing of structures.

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Introduction

In the future, large wind turbines will be placed offshore in considerable numbers. Since access will be difficult and costly, it is preferable to use monitoring systems to reduce the need for manual inspection. The motivation for the project is to create the fundamental basis necessary for the use of sensors as a structural health monitoring system for wind turbine blades. The project aims at creating knowledge that will allow sensor signals to be used for remotely identifying the position of damage, the damage type and severity, and generate a structural condition assessment of the wind turbine blades that can integrate with existing SCADA tools to improve management of large offshore wind farms, and optimise the manual inspection/maintenance effort.

This document gives an overview and breakdown of the work completed in project FU3101 (Fundamentals for remote condition monitoring of offshore wind turbines). It describes the progress of work within the five work packages, explaining the changes from initial objectives over the course of the project, the results achieved, and the future perspectives. The executive summary contextualises the technical output of this project (reports, papers and presentations), and presents its significance in influencing a broad spectrum of current activities in this area.

The partners in this consortium were Risø DTU (the Materials Research and Wind Energy departments), Force Technology, InnospeXion, Sensor Technology Center, NIRAS (Demex), and Siemens (Bonus Energy).

Summary

The motivation for this work is found in the developments of the wind energy industry, where the large offshore wind farms of the future require more advanced inspection and maintenance procedures. There are economic advantages possible if a network of sensors were capable of remotely assessing the condition of each individual turbine from an onshore central control station, and a physical inspection was only initiated when a specific repair requirement was identified. Remote monitoring of many other turbine components is common today, but blade assessment is still dominated by visual inspection which results in an expensive and time consuming operation with risks for missing sub-surface damage. The overall problem is a complex one and requires collaboration across various industrial sectors and academic disciplines. Any solution will be based on successfully combining various experimental and modelling approaches.

The three objectives with this project are;

Firstly	to develop a practical approach towards the use of sensors in remote monitoring applications of wind turbine blades
Secondly	to characterise different damage types based on sensor outputs
And thirdly	to develop an approach that can estimate the remaining life of a blade, based on the distribution of detected damage within it

In order to achieve these objectives it was decided to assign Work Packages (WPs) to investigate three sensor systems which had been identified in a previous project (FU1102) [1] as technically (and economically) capable of successfully detecting the early development of significant damage types in fibre reinforced composite, the material from which modern wind turbine blades are constructed.

In addition to these three sensor work packages, a fourth would develop the life-estimate approach and a fifth would involve application of sensors on a full-scale blade test. An overview of each of the five WPs is given in this document.

Hence,

WP1 Identifying damage types via acoustic emission (AE) signals

WP2 Testing the robustness of a fibre optic microbend transducer

WP3 Developing damage detection techniques using inertia sensors

WP4 Developing an approach for assessing blades with damage

WP5 Applying AE in a full scale fatigue test to blade failure

International interest in the application of remote sensing technology for the wind energy sector has dramatically increased recently. To the extent that the structural health monitoring research community, which previously had developed links with

the aerospace, civil engineering, and transport industrial sectors, now includes special sessions focussing on the way ahead for wind energy at all major conferences. This has led to an advantage for the project participants who have had an early focus on this emerging area allowing them to contribute well in recent discussion [2], [3].

A summary of the main results and perspectives from each of these Work Packages follows

Work Package 1

In the laboratory, “passive” AE sensing has been used as an aid to research into fracture mechanics by assisting in identifying the initiation and characterising the growth of different crack types in FRP sandwich specimens (foam and solid core). In this way the AE signal characteristics have been correlated with the amount of energy required to grow a particular crack [4],[5], this can have implications for assessing the severity of damage detected by a remote SHM system.

An “active” AE technique based on mobile sensors was proposed that aims to minimise the effect of external parameters when assessing damage condition [4]. Similarly, a simple technique using AE sensing has been proposed [6] that can be used on in-situ turbine blades to quickly identify those that contain (non-visible) damage and require an NDT inspection and repair assessment.

As a result of the investigations into the use of acoustic emission monitoring on wind turbine blades, the proposed methodology has been adopted for use in full scale test facilities, and by manufacturers/operators to provide a better understanding of structural responses under complex loading and in service. New product development agreements have been drafted to define future collaboration in this area, and initiatives to apply various sensor techniques on other structural types (such as bridges) are underway. Refining the application of sensing techniques in damage progression models and on tested and operating blades will continue to be a core research area for Risø DTU, with new large-scale test facilities specifically for structural components in the wind energy industry currently under construction. Direct collaboration with blade manufacturers and test facilities will help fully establish the new measurement and inspection technologies developed here into industrial application as effectively as possible.

A method of using AE sensors to determine the condition of wind turbine blades in service, described in [6], has now been put in practice as a trial inspection procedure. A portable AE sensor system is quickly attached inside the blade and a load artificially applied to the structure, any activity detected by the sensors indicates the presence of damage. A long term monitoring trial where AE activity generated by the in-service loading of the blade is continuously recorded and compared with the operating environment has also been successfully completed and will be reported soon.

Following this project, the development of a mobile sensor system for application in a wind turbine blade has been explored [7]. Such a system will lead to a practical demonstration of the effectiveness of an active sensor application similar to that suggested in task WP1.2 of this project [4], firstly as an aid to inspection and structural response analysis during proof testing (scheduled for later in 2008) and in the future as a system running in operational turbines. Furthermore the prospect of a movable AE sensing principle within the blade encourages the hope that after identifying the location of damage it will then be possible to position a sensor directly on that damage, thereby removing the effects of the structure and of material transmission on the detected waveforms. This makes it more likely that features successfully used to identify crack severity in laboratory specimens [4], [5] can also be obtained for damage present in structures loaded during operation.

An investigation has also begun on the more general topic of identifying factors affecting the adoption of new technology such as Structural Health Monitoring. This investigation will be undertaken in collaboration with AAUK (International Technology Management at Aalborg University) and will tackle the question "why do technologies succeed or fail?" using the context of SHM for wind turbine blades as a case study. In many cases, hindsight has made it clear why a particular technology failed. Is it, however, possible to make accurate predictions about whether or not a technology will succeed in advance? New information developed by this theoretical study can lead to a better long-term strategy for implementing SHM on wind turbine blades and help refine the evolutionary approach proposed in task WP1.3 of this project.

Work Package 2

The effectiveness of a new fibre optic microbend transducer sensor in acting as an embedded crack detector has successfully been investigated in a series of laboratory tests. The transducer was also proven to be insensitive to shear deformations and several design improvements were proposed following the laboratory trials [8]. However, due to a drop in price for various fibre optic sensor approaches, the project shifted focus from further development of the mircobend transducer, to reassess other sensor options including fibre bragg gratings, Fabry-Perot inferrometers, and new low-price interrogation units. Furthermore, various multiplexing schemes based on wavelength division multiplexing (WDM), time division multiplexing (TDM), and hybrid multiplexing systems were considered as was the possibility of using a wireless sensor system relevant to remote condition monitoring of wind turbine blades.

The decision taken to focus on trialling new “wireless” sensor systems for turbine blades (and other applications) has led to the formation of international consortiums and applications for European funding to develop a “Smart embedded sensor system” and “Self-powered Self-sensing Composite Materials for Structural Health Monitoring”, both projects scheduled to start in 2008.

Work Package 3

The modal analysis based approach to condition monitoring has proven to be a robust, reliable and relatively cheap method of providing basic information required of a structural health monitoring system, particularly providing promising perspectives for condition monitoring of wind turbine blades. As a built-in feature, it should be mentioned that only “essential” damages will give rise to (significant) modifications of the mode shapes, and the method thus implicitly includes a “filter” omitting insignificant damages. Therefore sensor fusion with other approaches (e.g. strain signals, velocity signals or displacement signals) is presupposed.

In order to identify structural characteristics of rotating wind turbine blades, it has been necessary to develop system identification approaches able to deal with linear periodic systems. A new class of *black box* system identification algorithms for linear periodic systems has been proposed that are numerically relatively handy. In addition, a *grey box* approach, combining a simplified elastic model of the rotating blade with an Extended Kalman filter, has been developed, and it has been demonstrated that the Extended Kalman filter can be used to estimate “transient” modal characteristics of a simulated, simplified wind turbine model during operation [9].

The proposed approaches are now to be tested against full scale data, with such tests planned within an ongoing project [Upwind] – involving both synthetic blade response data and full scale blade response data.

Work Package 4

The major failure modes in wind turbine blades have been reviewed and relevant material properties have been described. Some of the strength properties are easily measured. However, other properties are based on relative new concepts and new testing methods. The combination of structural health monitoring and modelling of blades with identified damage offers the possibility of predicting the growth of damage in wind turbine blades.

An outline is given for an approach for the determination of residual strength and the residual fatigue life of a wind turbine blade that has a well defined damage. The location of the damage can be identified by build-in sensors (structural health monitoring). The damage type and size can be determined by non destructive techniques. Modeling the blade with the damage, a fracture mechanics analysis can be conducted; the energy release rate is determined for maximum (static and cyclic) design loads. Coupled with relevant fracture data, the effect of the damage can be assessed. Tables are given for the most relevant failure modes and the appropriate failure properties, test methods for determination of the relevant strength properties are summarized and a literature survey is given containing 44 references to relevant and recent work in the areas of material models and materials test methods [10].

Work Package 5

A full scale turbine blade test has been conducted with real time monitoring from Acoustic Emission sensors. 18 different loading configurations of load location and blade orientation were undertaken and the different AE profiles for each configuration compared. Each load consisted of a stepwise increase in applied stress up to 150% of design load expected. Inspections using ultrasonic and x-ray techniques have been conducted to search for any subsequent damage development.

Experience has been gained, for both the sensor supplier and the blade manufacturer, in the practical application of the AE monitoring technique in such a way as to give an“activity profile” during the course of the testing. New insights have been reached as to the ways in which future testing (both specialised and standard) can benefit from new AE measurement possibilities. Furthermore, possible options for in-situ measurements for working turbine blades have been raised. The optimised use of modified inspection techniques, based on ultrasonic and x-ray, was successfully investigated during the blade testing [11].

One key conclusion from the activities in Work Package 5 was that commercial test facilities will always be under strong pressure to carry out vital certification testing for blades involving approved standard load applications. This naturally limits the options for trialling non-standard load types, monitoring systems, and NDT applications where commercial pressures act on the time and effort that can be added to what are already expensive test procedures.

The experiences in this project and others have convinced DTU that it is necessary to pursue investment in new research focussed test facilities capable of providing a multi-scale approach to material and structural response, damage identification and progression, monitoring and inspection technologies, and so on. Work is in progress to establish versatile sub-component and full-scale test facilities for wind energy (and other industrial) structures that will provide a unique research environment for deepening the understanding of composite material failure mode interactions from nano/microscale to the structural level (and similar problems in other structural materials). Such a facility will also support hybrid testing, where the test output from monitored sub-components interact in real-time with a computer simulation of the full structure, thus establishing intelligent boundary conditions for the tested component. The multifunctional aspect of the testing reflects the fact that industry is generally moving towards integrating and optimising several functions in the same structural component. The possibilities for advancing SHM technology using such an experimental facility are obvious.

Summary of major findings

- Practical approaches for using AE sensing on wind turbine blade structures have been demonstrated as effective in detecting the presence and extent of generic damage, both when conducting full scale blade tests and for in-situ application.

- Laboratory testing has indicated that detected AE waveform characteristics alone can be correlated to the fracture energy required when propagating crack growth in wind turbine materials and thus distinguish between different categories of damage event taking place within the polymer laminate and so rate the “severity” of that particular detected crack.

- The effectiveness of a new fibre optic microbend transducer sensor in acting as an embedded crack detector has successfully been investigated in a series of laboratory tests.

- A rapid drop in the total price of key fibre optic sensor approaches has improved the prospect of extensive utilisation of multiplexed Bragg grating sensors in future SHM systems.

- The modal analysis based approach to condition monitoring has proven to be a robust, reliable and relatively cheap method of providing basic information required of a structural health monitoring system, particularly providing promising perspectives for condition monitoring of wind turbine blades.

- A new class of *black box* system identification algorithms for linear periodic systems has been developed, in addition to a *grey box* approach combining a simplified elastic model of the rotating blade with an Extended Kalman filter.

- A new approach to determining the residual strength and fatigue life of damaged wind turbine blades in service has been outlined based on all the latest research into the relevant structural failure modes and polymer composite material properties.

- The optimised use of modified Non-Destructive Testing inspection techniques, based on ultrasonic and x-ray, can contribute to improving all standard blade test procedures.

Suggestions for future work

- A practical demonstration of the suggested mobile sensing principle during full scale blade tests should be undertaken in order to establish how effective the active AE “scanning” system described in this project is in normalising the effects of non-damage factors on returned waveforms in an Acoustoultrasonic system, and to investigate the extent of other benefits possible by automatically placing an AE sensor directly on any detected structural damages.

- The proposed system identification approaches should now be tested against full scale data involving both synthetic blade response data and full scale blade response data.

- Purpose built large-scale test facilities exclusively for research purposes are required in order to fully investigate the application of various sensing techniques as part of a far wider effort towards improved understanding of the effect of damage in structures.

- A more general investigation of the factors that contribute to the adoption of new technologies using the application of structural health monitoring on wind turbine blades as a case study.

- Projects trialling new approaches for wind turbine blade SHM systems based on low powered, wireless sensor technology utilising energy scavenging techniques.

- Technical definition of the logical node classes and data classes for all relevant blade sensing approaches within the new industrial data tool standardisation effort covered by IEC 61400-25 Part 6.

- A comparison of strength predictions made using strength properties from laboratory test specimens, with experimental results from structures involving differing sizes and geometries.

- Extensive investigation into the effect of large scale bridging on cyclic crack growth, both in characterisation and modelling.

Resumé

Baggrunden for dette arbejde stammer fra udviklingen i vindenergiindustrien hvor fremtidens store havvindmølleparker vil kræve mere avancerede inspektions- og vedligeholdelsesprocedurer. Der er mulige økonomiske fordele hvis et netværk af sensorer er i stand til at vurdere tilstanden hos de enkelte vindmøller fra en central kontrolstation, og der derfor kun skulle iværksættes fysiske inspektioner hvis et behov for en specifik reparation blev fundet. I øjeblikket er fjernovervågning af mange andre komponenter på vindmøllerne almindelig, men vurderinger af selve vingernes tilstand baseres stadig oftest på visuel inspektion. Disse inspektioner er både dyre og tager lang tid, og der er en risiko for at overse skader der ikke er synlige på vingernes overflader. Det overordnede problem er komplekst, og kræver samarbejde på tværs af flere industrielle sektorer og akademiske discipliner. Eventuelle løsninger vil være baserede på en kombination af forskellige eksperimentelle og modelbaserede tilgange.

De tre mål med dette projekt er:

For det første	At udvikle en praktisk tilgang til brugen af sensorer i fjernmonitorering af vindmøllevinger.
For det andet	At karakterisere forskellige typer af skader, baseret på sensorernes output.
Og for det tredje	At udvikle en metode til, baseret på fordelingen af detekteret intern skade, at vurdere en vinges resterende levetid.

For at opnå disse mål blev det besluttet at oprette arbejdspakker (Work Packages, WP) for at undersøge tre sensor systemer som i et tidligere projekt (FU1102) var blevet bedømt som teknisk og økonomisk i stand til at opdage den tidlige udvikling af forskellige typer af skader i fiberforstækede kompositmaterialer, det materiale som moderne vindmøllevinger er lavet af.

Ud over de tre arbejdspakker der angik sensorerne, ville en fjerde udvikle tilgangen til at vurdere levetiden, og en femte ville beskæftige sig med anvendelsen af sensorer i en fuldskala test af vingerne.

Derfor:

WP1	Identifikation af forskellige typer af skader gennem akustisk emission (AE)
WP2	Test af hvor robuste fiberoptiske microbend transducere er
WP3	Udvikling af system til opdagelse af skader, baseret på inerti sensorer
WP4	Udvikling af en metode til at detektere beskadigede vinger
WP5	Anvendelse af AE under fuldskala udmattelsestest

Den internationale interesse for anvendelse af fjernbetjent sensorteknologi i vindenergisektoren er vokset dramatisk i de senere år. Det er kommet så vidt at de der beskæftiger sig med overvågning af strukturel integritet (Structural Health Monitoring, SHM), og som tidligere har udviklet kontakt til luftfartsindustrien, byggesektoren, og transportindustrien, nu har specielle sessioner ved alle større konferencer hvori de fokuserer på fremtiden. Dette har været en fordel for alle deltagere i projektet, da de har haft et tidligt fokus på dette voksende område, og de har derfor været i stand til at bidrage med meget i de seneste diskussioner.

Her følger at resumé af de vigtigste resultater og perspektiver fra hver af de nævnte arbejdspakker:

Arbejdspakke 1 (WP1)

I laboratoriet har ”passive” AE sensorer været brugt til at hjælpe til ved forskning i brud. AE sensorerne har været til hjælp ved identificering og karakterisering af hvordan forskellige brudtyper i FRP sandwich prøver (skum- og solid kerne) er startet og vokset. På den måde er AE signalkarakteristikker blevet sammenstillet med den mængde energi der er påkrævet for at en bestemt revne er vokset. Dette kan have implikationer for at vurdere omfanget af skader som er opfanget af fjernbetjente SHM systemer.

Det er blevet foreslået at udvikle en ”aktiv” AE teknik baseret på mobile sensorer, og på den måde minimere effekten af eksterne faktorer når en skade vurderes. På samme måde er der forslag om en simpel teknik med AE sensorer der kan indbygges i vingerne for hurtigt at identificere vinger som har usynlige skader, og som derfor kræver en NDT inspektion og en vurdering af reparation.

Som et resultat af undersøgelserne af brugen af AE baseret overvågning af vindmøllevinger, er den foreslåede metodologi blevet taget i brug ved fuldskala testfaciliteter, og af producenter og brugere, for at give en bedre forståelse af strukturelle reaktioner på komplekse belastninger og i drift. Der er planlagt nye produktudviklingsaftaler for at definere fremtidigt samarbejde inden for området, og der er initiativer undervejs som skal benytte forskellige sensorteknikker på andre typer af strukturer, eksempelvis broer.

Forbedring af anvendelsen af sensorteknikker på skadeudviklingsmodeller, og på testede vinger og vinger i brug vil fortsat være et kerneområde for forskningen på Risø DTU, med de nye storskala testfaciliteter der er ved at blive bygget specifikt til strukturelle komponenter hos vindenergiindustrien. Et direkte samarbejde med producenter af vinger med testfaciliteter vil hjælpe med fuldt ud at etablere de hér udviklede nye målings- og inspektionsteknikker i industriel anvendelse så effektivt som muligt.

En metode til at bruge AE sensorer til at bestemme tilstanden af vindmøllevinger i brug, som beskrevet i [6], er nu blevet effektueret, først som test, og senere som en næsten standard inspektionsprocedure. Et AE system bliver hurtigt sat fast indeni i vingen, og strukturen bliver kunstigt belastet. Hvis AE måler aktivitet, tyder det på tilstedeværelsen af skader. Overvågning forgår over lang tid, hvor AE aktivitet som resultat af belastningen ved drift bliver kontinuerligt overvåget, er også blevet gennemført med succes, og der vil snart foreligge en rapport om dette emne.

Som følge af dette projekt, er der forsket i udviklingen af et mobilt sensor system til brug i vindmøllevinger. Et sådant system vil føre til en praktisk demonstration af effektiviteten af en aktiv sensor applikation, som foreslået i opgave WP1.2 i dette projekt [4]. Først som en støtte til inspektion af strukturelle reaktioner ved prøve tests (bliver udført senere i 2008), og i fremtiden som et system i vindmøller i drift. Yderligere er fremtidsudsigten med bevægelige sensorer inden i vingen håbet om at sensoren, efter at skaden er lokaliseret, kan flytte sig hen til hvor skaden er sket, og på den måde fjerne effekterne af strukturen og på transmissionen gennem materialet på de detekterede bølger. Dette gør det mere sandsynligt at metoder, der med succes er benyttet til at identificere betydningen af revner på laboratorieprøver, også kan benyttes på strukturer i drift.

Der er også iværksat en undersøgelse der beskæftiger sig med det mere generelle emne der omhandler de faktorer der påvirker indførelsen af ny teknologi såsom SHM. Denne undersøgelse bliver foretaget i samarbejde med AAUK (International teknologiledelse på Aalborg Universitet), og vil beskæftige sig med spørgsmålet ”hvorfor ender teknologier som succeser eller fiaskoer?” Brug af SHM for vindmøllevinger benyttes som en case study. Det er ofte sådan at det i bagklogskabens lys er let at se hvorfor en teknologi er blevet en fiasko, men spørgsmålet er om det på forhånd er muligt at vurdere om en teknologi bliver en succes eller ej. Den nye information der fremkommer i dette teoretiske studie kan føre til en bedre langsigtet strategi for implementering af SHM på vindmøllevinger, og kan hjælpe til med at raffinere den evolutionære tilgang der er foreslået i opgave WP1.3 i dette projekt.

Arbejdspakke 2 (WP2)

Det er gennem laboratorietests lykkedes at vurdere effektiviteten af en ny fiberoptisk microbend transducer sensor som en indbygget måde at opdage revner på. Det er også påvist at transduceren
ikke er følsom overfor forskydningensdeformationer (shear), og der blev i øvrigt foreslået flere forbedringer efter laboratorietestene [8]. Grundet prisfald på forskellige fiberoptiske sensorer, skiftede projektet imidlertid fokus væk fra yderligere udvikling af microbend transduceren. Dette skete for at vurdere andre muligheder såsom fiber bragg gratings, Fabry-Perot inferometre, og nye billige undersøgelsesmoduler. Ydermere blev forskellige multiplex baserede løsninger overvejet, nemlig løsninger baseret på wavelength division multiplexing (WDM), time division multiplexing (TDM), og hybrid multiplexing, så vel som muligheden for at benytte trådløse sensor systemer der er relevante for fjernovervågning af vindmøllevinger.

Beslutningen om at lægge fokus på at afprøve nye ”trådløse” sensor systemer har ført til dannelsen af internationale konsortier og ansøgninger om Europæisk finansiering til udviklingen af et ”intelligent indbygget sensor system” og ”selv-drevne og selv-sansende kompositmaterialer til SHM”. Begge projekter har planlagt start i 2008.

Arbejdspakke 3 (WP3)

Benyttelsen af modalbaserede analyser til tilstandsovervågning har vist sig at være en robust, pålidelig, og relativt billig måde at skaffe den basale information der kræves af et SHM system, især i forbindelse med at overvåge tilstanden af vindmøllevinger. Som en indbygget funktion, er det værd at nævne at der skal

”afgørende” skader til før der sker (betydelige) ændringer af modus formerne, og at denne metode derfor har en slags indbygget ”filter” der ser bort fra ubetydelige skader. På den baggrund er det at forudsige en fusion af disse typer af sensorer med andre input (fx stress signaler, hastigheds signaler eller forskydningssignaler).

For at identificere strukturelle karakteristikker på roterende vindmøllevinger, har det været nødvendigt at udvikle en metode til systemidentifikation der er i stand til at håndtere lineære periodiske systemer. Der ligger forslag om en ny klasse af *black box* systemidentifikationsalgoritmer til lineære periodiske systemer. Disse er rent numerisk relativt nemme at have med at gøre. Ud over det er der blevet udviklet en *grey box* metode, som kombinerer en simplificeret elastisk model af den roterende vinge med et udvidet Kalman filter. Det er blevet demonstreret at det udvidede Kalman filter kan bruges til at bedømme ”transiente” modelkarakteristikker af en simuleret og simplificeret vingemodel i drift.

De foreslåede metoder skal testes mod fuldskala data. Sådanne tests er planlagt i et projekt der allerede er i gang [Upwind]. Det involverer både syntetiske data for vingernes reaktioner og fuldskala data.

Arbejdspakke 4 (WP4)

De vigtigste fejltyper på vindmøllevinger er blevet undersøgt, og de relevante materialeegenskaber er blevet beskrevet. Nogle af styrkeegenskaberne er lette at måle, men andre er baseret på relativt nye koncepter eller testmetoder. Kombinationen af SHM og modellering af vinger med identificerede skader giver mulighed for at forudse væksten i skader på vindmøllevinger.

Der er blevet udarbejdet en skitse for en metode til at fastsætte resterende styrke og resterende levetid for en vinge der har veldefinerede skader. Placeringen af skaden kan fastsættes ved hjælp af indbyggede sensorer (SHM). Skadens type og størrelse kan bestemmes ved hjælp af ikke-destruktive teknikker. Ved at lave en model af vingen med skaden, kan en fraktur-analyse udføres. Raten af energifrigivelse kan fastsættes for maksimum (statisk og cyklisk) belastninger af designet. Sammenholdt med de relevante bruddata kan effekten af skaden vurderes. Der er lavet tabeller for de mest relevante fejltyper og de tilhørede fejlegenskaber, der beskrevet testmetoder til fastslåelse af de relevante styrkeegenskaber, og der er udarbejdet et overblik over relevant litteratur, inklusive 44 referencer til det seneste arbejde indenfor områderne materialemodeller og testmetoder til materialer.

Arbejdspakke 5 (WP5)

Der er blevet udført en fuldskala test af vindmøllevinger med overvågning i realtid fra akustisk emission sensorer. Der blev udført tests af 18 forskellige belastningskonfigurationer og placering af vingerne, og de forskellige AE profiler for hver konfiguration blev sammenlignet. Hver test bestod af trinvist øgede belastninger, op til 150% af den forventede design belastning. Efterfølgende er der blevet udført inspektioner med ultrasoniske- og røngten-teknikker for at undersøge for efterfølgende udvikling af skader.

Både sensor leverandøren og af vinge producenten har gjort erfaringer indenfor den praktiske brug af AE overvågningsteknikker så de kan give en ”aktivitetsprofil” gennem testen. Det er også lykkedes at opnå ny indsigt i hvordan fremtidige tests (både specialiserede og standard) kan drage nytte af de nye muligheder med AE målinger. Derudover er der mulighed for at lave tests der er indbygget i vindmøllevingerne. Den forbedrede brug af modificerede inspektionsteknikker, baseret på ultralyd og røngtgen, blev undersøgt med succes under testen af vingerne.

En af de vigtigste konklusioner fra aktiviteterne i arbejdspakke 5 var at, under normale forhold, kommercielle testfaciliteter vil altid være under stort pres for at udføre de vitale certificeringer der er forbundet med godkendelse. Dette medfører helt naturligt at ikke-standard test, såsom usædvanlige belastningstyper, overvågningssystemer og brug af NDT, kan medføre yderligere omkostninger til de i forvejen dyre testprocedurer.

De erfaringer der er gjort i dette projekt har overbevist DTU om at det er nødvendigt at investere i ny forskning med fokus på testfaciliteter der kan give en multiskala tilgang til materialers og strukturers reaktioner, identifikation af skader og deres udvikling, overvågnings- og inpektionsteknologier, osv. Der bliver arbejdet på at etablere alsidige underkomponents- og fuldskala testfaciliteter til vindenergiens strukturer (og tilsvarende). Disse vil give et unikt forskningsmiljø der giver mulighed for en dybere forståelse af kompositmaterialers fejlegenskaber, fra et nano elller mikroskala, op til strukturelt niveau. En sådan facilitet vil også give mulighed for hybrid tests, hvor output fra overvågning af underkomponenter vil vekselvirke med computersimuleringer af hele strukturen i realtid, og på den måde fastslå intelligente grænseværdier for den testede komponent.

Testenes multifunktionelle natur afspejler det faktum at industrien generelt set bevæger sig mod at integrere og forbedre flere forskellige funktioner i den samme strukturelle komponent. Mulighederne for at forbedre SHM teknologien i en sådan afprøvningsfacilitet er åbenlyse.

Resumé af centrale resultater

- Praktisk anvendelse af akustisk sensorer på vindmøllervinger er blevet demonstrer som effektive til at lokalisere aktuelle skader i strukturerne, både ved testing og i almindelig brug.

- Laboratory tests har indikeret at AE signaler alene kan korrelere til energi ved tiltagende revner/brud i vindmøllevinge materialer. På den måde kan vi skelne mellem forskellige kategorier af skader i polymer laminat og derved bestemme ”alvoren” i en særligt fundet skade.

- Laboratorieforsøg har demonstreret at en ny optisk microbend transducer er effektiv som indbygget revnesensor.

- De seneste års prisfald på fiberoptiske sensorsystemer har forøget interessen for at bruge multiplexed Bragg Grating sensorer i fremtidens SHM systemer.

- Modal analyse-baseret tilstandsovervågning har vist sig at være en robust, pålidelig og relativ billig metode til at give basis information om vindmøllevingers tilstand.

- En ny type af ”black box” system identifikation algoritmer for lineare periodiske systemer er udviklet. Der er også udviklet en ”grey box” model som kombinerer en simpel elastisk model af roterende vinger med et udvidet Kalman filter.

- En ny måde at bestemme rest styrken og levetiden på skadede vindmøllevinger i brug er beskrevet. Den baserer sig på den seneste forskning indenfor strukturelle skadesmekanisme og materialeegenskaber af plastkompositter.

- Den optimerede anvendelse af nye Ultralyd- og Røntgenteknikker kan bedrage til en forbedret testprocedure for vindmøllevinger.

Forslag til fremtidigt arbejde

- En praktisk demonstration af det mobile sensorsystem skal udføres på en fuld-skala test. Denne demonstration skal vise hvor effektiv sådan et ”Acoustoultrasonic” system er til at udskille faktorer der ikke stammer fra skaderne. Ved at placere sensorerne tættere på skaden åbnes der mulighed for at karakteriser skades typen.

- Det nye modelanalysesystem skal afprøves med fuldskala data – både matematiske model data og målte data fra en vinge i brug.

- Der er behov for nye store forsøgsfaciliteter der henvender sig til forsknings formål. Dermed kan der forskes mere i anvendelsen af forskellige sensorteknikker som led i en bredere forståelse af skadesmekanismerne i konstruktioner.

- En generel undersøgelse af de faktorer der bidrager til udnyttelsen af nye teknologier med SHM på vindmøllevinger som case study.

- Gennemføre projekter der fokuserer på mulighederne med nyt udstyr indenfor lavenergi trådløs sensorteknik.

- Definere hvordan information fra vingesensorerne integreres i den nye IEC standard for datakommunikation for vindmøller (IEC61400-25 Part 6).

- En sammenligning mellem de forudsigelser der stammer fra laboratorieforsøg og eksperimentelle resultater fra strukturer af forskellig størrelse og geometri.

- Omfattende undersøgelser af effekten af ”large scale bridging” i vækst på cyklisk belastede revner – både eksperimentel karakterisering og matematisk modellering.

Work Package 1

Identifying damage types via acoustic emission (AE) signals

This section reports work performed in Work Package 1 (WP1) of the PSO-F&U project entitled "Fundamentals for remote condition monitoring of wind turbine blades (Phase II)" dealing with the identification and characterisation of damage using output from Acoustic Emission (AE) monitoring.

Acoustic emission is a monitoring technique that has previously been identified in the phase I project [1] as capable of detecting very small damages and that could be used to economically locate the position and size of evolving damage in the operating turbine blade [12].

In phase II, the overall goal of Work Package 1 is to further demonstrate that passive AE sensors also have the perspective of distinguishing between different categories of damage event taking place within laminate fibre-polymer composite materials tested in the laboratory. In addition, the sensor signals should permit an estimate of how "serious" the detected damage is by mapping it to a material property (see WP4) and relating the location of the damage to known structural models.

A secondary objective was to investigate methods for using acoustoultrasonics (active AE) that would minimise the effect of external parameters, maximise the detection limit for any damage present, and would be suitable for use on a wind turbine blade.

Sub-tasks in Work Package 1

The three sub-tasks in this work package are briefly described in the following.

- WP1.1

Differentiate between different damage types via a series of mechanical tests that simulate the growth of damage within the laminate and along the adhesive interface between two composite layers.

- WP1.2

Acoustoultrasonic (Active AE) investigation to establish a damage detection technique that minimises the influence of external parameters affecting signal transmission/detection.

- WP1.3

Assessment of the significance of AE activity in a wind turbine blade begins with the level of overall activity and any changes/exceptions from established levels. More advanced forms will use AE waveform characteristics to distinguish between stable and unstable growth of damage.

Over the course of the project the application of AE sensors on blades in-situ was also discussed and a method suggested (and later demonstrated) for an inspection technique involving an array of sensors mounted inside the structure. This technique can be compared with manual inspections using ultrasonic and/or x-ray equipment, however the prospect exists of allowing the installed AE sensors to continue to gather data during service and monitor the growth of any damage during normal operation.

Challenges

It was known from the phase I project that the growth of damage in wind turbine blades generated stress waves that could be detected by surface mounted AE sensors. An array of these sensors would then be suitable to provide a qualitative indication of when and where damage occurred in the blade relative to loading conditions (mechanical loading during testing or wind loading during operation). This is an example of the sensor being used in a “passive” mode, where the sensors return energy released from within the structure itself.

The polymer composite material used in wind turbine blade structures is formed by consolidating laminate layers (and sandwich core material) together. The most significant progressive failure type is the loss of this laminate integrity. There are huge differences in the damage tolerance calculations used when determining the “severity” of a crack based on its position through the thickness of the laminate structure; whether it is a delamination, debond (interface crack), core failure, and so on (see figure 1).

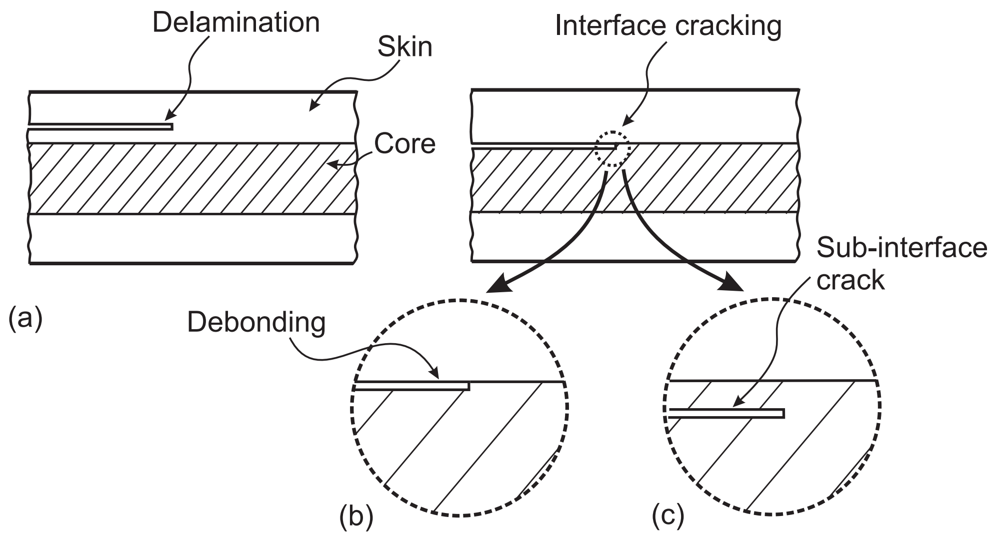


Figure 1. Basic cracking modes in sandwich structures:
(a) cracking in the skin,
(b) interface debonding and
(c) cracking in the core material.

Furthermore, the through-thickness laminate position of a crack detected by an Ultrasonic or X-ray scan is often difficult to resolve. Pulse echo ultrasonic inspection for example will register a similar “loss of transmission” for both debonds and delaminations, and as the difference in depth between these two damage types might only be a matter of millimetres making a distinction between them is not always easy.

These are the reasons why the particular damage types specified for investigation and characterisation in task WP1.1 are; growth of damage (cracking) within the laminate (*delamination*) and growth of damage (cracking) along the adhesive interface between two composite layers or a composite and core material (*debonding*).

In task WP1.2, the application of the acoustoultrasonic technique is considered. Here the AE sensors can be used in an “active” mode where one is used to impart a controlled excitation into the composite structure in order to create a mechanical disturbance within the material. At the same time, other transducer sensors at other locations in the structure sense the resulting vibrations (ultrasonic waves) caused by the disturbance.

The presence of various defects and damages in the structural material between the active and passive sensor pair will alter the waveform returned by an acoustoultrasonic inspection. Structural Health Monitoring systems based on active AE sensing are not uncommon in aerospace technology demonstrator programs [13], [14]. The sensor/transmitters are mounted on (or embedded within) the structure and during operation they are used to generate waveforms. These generated waveforms are then compared with “template” waveforms that were previously generated by the system, usually shortly after installation. Differences between the operation generated waveforms and the templates are intended to be indicative of the presence of damage between the transmitter and the receiver [15], [16].

However, a serious problem with this approach is the number of other factors that affect the wave propagation in the material and which cannot be easily controlled away from laboratory conditions. Factors such as ambient temperature, water content, background noise, material age effects, structure operation, etc. The result is that the generated waveforms differing from the template were often due too factors other than the presence of damage. The challenge in task WP1.2 was to investigate a method that would minimise the affect of these other factors and thus improve the damage detection capability when using active AE (acoustoultrasonics)

A huge amount of information is potentially available from active and passive AE sensing on a wind turbine blade structure. Acoustic emission sensors are capable of detecting the release of tiny amounts of energy corresponding to the smallest damage types, and each detected waveform contains features that might provide characterising information about the nature of the damage that generated it if those features could be reliably extracted from the other factors. In the laboratory (task WP1.1) some simple feature extraction is possible using small-scale test specimens under specific and controlled loading conditions.

But in a larger structure under dynamic loading, feature extraction of this kind would be far from straightforward and simpler applications of AE monitoring returning general structural response information must be the initial target. It is the challenge in task WP1.3 to establish the framework of this “gradient” of AE structural monitoring; where simple, robust, and practical implementations are put forward and demonstrated as suitable for use now. And plans to establish increasingly more developed and capable SHM systems are initiated and demonstrated in the laboratory.

Practical work and results

Double Cantilever Beam (DCB) crack growth specimens were extracted from the polymer fibre composite / foam core sandwich material of a wind turbine blade. Using laboratory test machinery specifically designed to be capable of controlling the applied bending moment, it was possible to generate crack growth displaying different fracture characteristics in a series of identical test specimens.

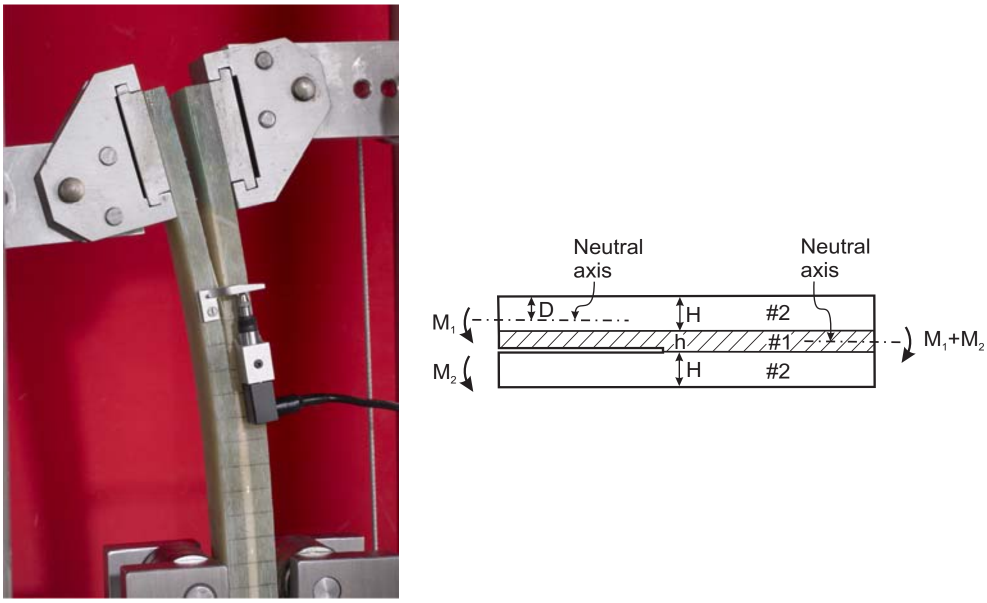


Figure 2. Image showing a DCB test specimen under mixed mode load

In order to clarify the understanding of the materials crack behaviour under different mode mixity conditions, it was expected that the AE data would highlight damage initiation and location of the crack front during the static loading and subsequent crack propagation in each DCB specimen. The AE characteristics recorded were also expected to reflect the different types of crack generated in the material.

As well as highlighting general differences in the AE activity profiles for the crack growth, the tests also showed a quantitative relationship between the AE activity being detected in real-time and the level of fibre bridging present in an advancing crack. This is significant as the level of fibre bridging in a polymer composite laminate delamination or debond determines the cohesive zone value used to calculate fracture toughness in basic fracture mechanical models for sandwich polymer composites.

A second series of tests were conducted on two different sets of DCB specimens, one where delamination within the skin material was generated, and another where debonding of the skin/core interface was the failure mode. For both these sets, great care was taken to link the AE detected to the actual loading/crack growth conditions at that time; for example, load increasing, load steady, mode I crack advance, mode II crack advance, unloading, friction in existing crack, and so on. In this way it was hoped to obtain a better comparison of the relationship between the acoustic emission signals and damage development.

Various AE signal ratios obtained were compared, from the different test sets (skin material and sandwich material), damage types (delamination and debonding), crack opening modes (mode I and II), and crack growth characteristic (sudden or steady state). This revealed a huge range of values. From the results it was clear that despite the fact that these differences had an effect on the AE emitted, it was only by considering several aspects of the AE emission simultaneously that it would be possible to establish the patterns that allow real-time identification of events from the AE signals being detected. Analysis of this kind is common in research using neural networks.

As well as using the passive sensing functions of AE sensors to detect, locate, and characterise the movement of damage (task WP1.1), the project also considered how best to implement active sensing approaches using these sensor types (task WP1.2). In order to circumvent the problem of factors other than damage affecting the returned response in an active AE array, it is necessary to either provide models that allow a deconvolution of the effect of these other factors from the received waveform (and these factors must also be measured each time the system is used), or to create a data normalisation where the so-called "template" signal automatically takes account of these other factors, and can still detect the presence of damage as a novelty event.

It was decided that the simplest approach to try would be where data normalisation is achieved by making a linked transmitter/receiver pair that could be swept across a section of the structure taking measurements for the entire length. This scan will return a waveform profile based on the wave propagation effects that exist in the material at that time; if these conditions are constant along the length of the material and for the duration of the sweep then no significant difference in the waveform will be observed. Therefore, known variables such as reinforcement lay-up, material type, structure effects, sensor/transmitter separation, etc., can be accounted for by the scan; whereas material age, water content, ambient temperature, transmitted signal, receiver frequency response, background noise, etc. are all assumed to be constant along the length of the section.

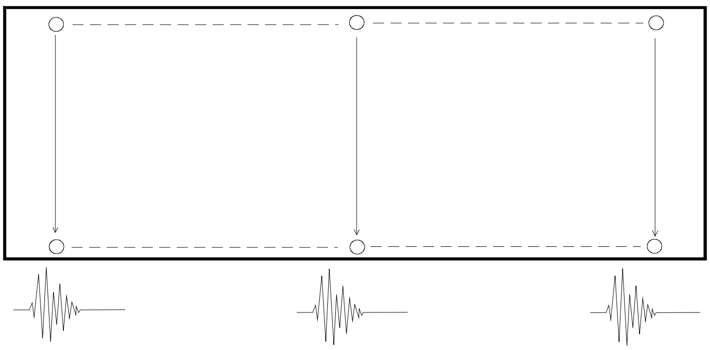


Figure 3. Schematic showing an active AE scan of an undamaged panel

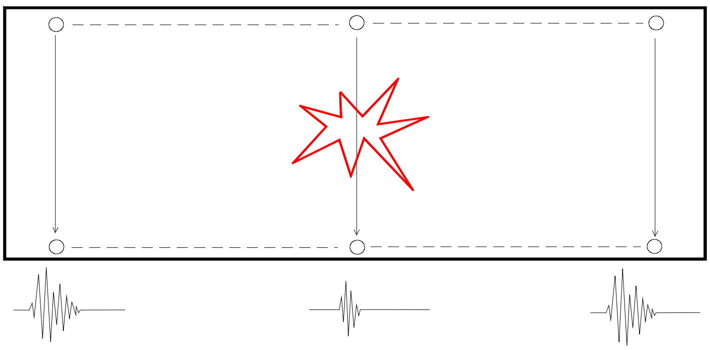


Figure 4. Schematic showing an active AE scan of a panel containing a damaged area

A simple approach of this kind (based on the sensoric range of a sensor) has been used for many years during full scale testing of wind turbine blades where a series of measurements along the length of the structure is used to highlight sections where damage has begun to develop. For example, areas of the structure with poor skin/core bond quality will have a far greater attenuation rate and hence a lower sensoric range. The sensoric range data thus obtained correlates well with bond quality along the length of the structure and hence can be used to quickly identify areas of damage and sections where damage has developed since the last inspection. These new damage areas can then be inspected and documented in more detail using visual and ultrasonic techniques. A system capable of performing a similar check automatically could be used to generate a profile of material quality along the length of a test blade (or in an operating blade).

In general, when monitoring the acoustic emission from a large test structure like a wind turbine blade, it is sufficient to use a zonal localisation where the first sensor to detect a particular event is used to localise that event within a section of the structure corresponding to the sensoric range. This method is simple, allows the greatest volume of structure to be monitored, and in most cases is detailed enough for the monitoring purpose. However, in situations where more accurate localisation information is required a triangulation based on time of flight information from sensors with overlapping sensoric ranges can be used. More detailed information of this kind can uncover the precise source of activity within the structure, the pattern of activity, the energy released by the signal, etc. From this a more precise interpretation of the damage condition can be attempted.

Wind turbine blades have orthotropic characteristics and for this reason a triangulation algorithm assuming isotropy will often lead to errors. Part of the work in WP1 involved developing and testing an algorithm capable of accommodating the special properties of composite materials.

The laboratory testing of composite specimens has shown that AE sensors can be used to provide information about the crack growth that allows us to discriminate between different crack types and estimate the energy required to grow the crack (task WP1.1). Extensive full scale testing of wind turbine blades has shown the value of zonal AE sensing for indicating the general structural response of the blade and providing “exception analysis” in cases where the presence of damage increases AE activity relative to the undamaged state ([17], [18], [19], [20] and [21]).

When considering how best to approach an on-line instrumentation of a working turbine blade it is suggested to consider a scale of potentially useful information. Whereby AE profiling similar to that used during blade testing can determine changes in structural operating environment (exception analysis), then with some application, based on laboratory investigations, use the same data to determine changes in “generic damage” condition, provide more precise localisation, and ultimately including the most complex of tasks such as determining the key material parameters of the damage type causing the activity. This damage condition characterisation by sensors will only become the basis for a viable (high-capability) Structural Health Monitoring System when detailed models are also developed that couple the global structural response of the blade under various operating loading conditions with knowledge of the material parameters that dominate growth characteristics of different defect/damage types.

The ultimate ambition of the authors is at the high end of this scale and is therefore complex, but using an evolutionary approach to system development it is possible to demonstrate simple instrumentations that can immediately provide assistance to the current maintenance/inspection operations. And whilst these instrumentations fall short of the full automation characterised by high capability SHMS, they can be used to develop the knowledge required, and increase the confidence in, the progressively higher capability systems that will follow.

The results of the laboratory investigations into the passive and active applications of AE sensors to detect and characterise damage in wind turbine blade materials are described in [4]. The in-situ blade assessment method using AE that was developed during the project is described in [6], this is an internal report containing information classed as “commercial-in-confidence”. During the project, parts of the work in WP1 were also presented at International conferences on Structural Health Monitoring in 2004 [5], 2006 [22] and 2007 [2].

Conclusion and future perspectives

In the laboratory, AE sensing has been used as an aid to research into fracture mechanics by assisting in identifying the initiation and growth of different crack types in FRP sandwich specimens (foam and solid core). In addition to this, it has been shown that the AE characteristics during crack growth reflect

- the amount of fibre bridging
- the mode mixity
- the location of the crack within the layered structure

In this way the AE signal characteristics have been correlated with the amount of energy required to grow the crack. From this it is proposed that an assessment of the crack type present in such a specimen can be made purely on the basis of sampling AE data obtained during loading. It is further proposed that any changes in the type of crack occurring during the test can be noted and identified using only the AE record. In this way a “real-time” AE output during the test would use features of the waveform characteristics from the specimen crack growth to indicate whether microscale (fibre bridging) or macroscale damage evolution was taking place.

A damage tolerance approach for any structure needs to consider the location of an area of damage, the activity of that damage and the severity of that activity in relation to the particular structural location. One of the key considerations when assessing severity is the energy uptake, how much energy is required to grow the damage. Despite the many practical problems that would require to be investigated, an approach based on AE sensing can be proposed that “rates” the severity of the activity from a particular area of damage in a polymer GRP sandwich panel by comparing the ratio of microscale to macroscale events during in service loading. In this way the energy uptake required to grow the damage could be estimated and the criticality calculated using established laws of fracture mechanics. In particular, applications for damage assessment sensing in wind turbine blades are of interest as such an approach can minimise invasive repair activity on detected areas of damage that are not immediately threatening to normal structural operation.

The method of using AE sensors to investigate the condition of wind turbine blades in service (described in [6]) is now undergoing further trial on operating turbines. A portable AE sensor system is quickly attached inside the blade and a load artificially applied to the structure, any activity detected by the sensors indicates the presence of damage. A long term monitoring trial where AE activity generated by the in-service loading of the blade is continuously recorded and compared with the operating environment has also been successfully completed and will be reported soon.

Following this project, the development of a mobile sensor system for application in a wind turbine blade (during proof testing and in operation) has subsequently been explored in [7]. Such a system will lead to a practical demonstration of the effectiveness of an active sensor application similar to that suggested in task WP1.2. Furthermore the prospect of a movable AE sensing principle encourages the hope that after identifying the location of damage (with embedded sensors) it will then be possible to position a sensor directly on that damage. Thereby removing the effects of the structure and of material transmission on the detected waveform by placing the sensor as close to the growing damage as possible. This makes it more likely that features successfully used to identify crack severity in laboratory specimens [4], [5] can also be obtained for damage present in structures.

An investigation has also begun on the more general topic of identifying factors affecting the adoption of new technology such as Structural Health Monitoring. This investigation will be undertaken in collaboration with AAUK (International Technology Management at Aalborg University) and will tackle the question "why do technologies succeed or fail?" using the context of SHM for wind turbine blades as a case study. In many cases, hindsight has made it clear why a particular technology failed. Is it, however, possible to make accurate predictions about whether or not a technology will succeed in advance? New information developed by this theoretical study can lead to a better long-term strategy for implementing SHM on wind turbine blades and help refine the evolutionary approach proposed in task WP1.3

Work Package 2

Testing the robustness of a fibre optic microbend transducer

This section reports work performed in Work Package 2 (WP2) of the PSO-F&U project entitled “Fundamentals for remote condition monitoring of wind turbine blades (Phase II)” dealing with the development and testing of a fibre optic microbend transducer for crack detection.

In the previous project [23] a fibre optic displacement transducer was designed and tested that could detect damage in the adhesive layers of wind turbine blades. The transducer was based on the fibre optic microbend principle. The pre-project reported the results of measurements and optical simulations of light transmittance through optical fibres with micro-bends, and a suggestion was made for a design suitable for use in this application. Four transducer prototypes were then manufactured based on this design and tested in a controlled full scale test blade where damage in the adhesive layer was propagated.

The overall goal of WP2 is to push forward with the development of a fibre optic based displacement transducer based on a microbend sensor embedded in the adhesive layer between two wind turbine blade structural components. An improved design approach is needed and more comprehensive testing in laboratory test specimens must be done to establish the sensitivity of the transducer and the effect of non-perpendicular displacements.

Subtasks in Work Package 2

- WP2.1

Characterisation of the sensitivity of the microbend transducer using calibration tools and an assessment of the effect of non-perpendicular displacement on the sensor

- WP2.2

Mechanical testing of an adhesive layer using the embedded prototype microbend transducer to detect the crack growth

- WP2.3

Assessment of the effect of the embedded sensor on the growth characteristics of the adhesive layer cracking

- WP2.4

Improvement of the sensor design

Challenges

The previous project (FU1102) suggested that the fibre optic microbend transducer was a promising sensor type for development in the follow-on FU3101 project [12]. This assertion was partly based on the prohibitive costs involved in the processing and application of other relevant fibre optic sensor types. The drastic fall in the cost of these other sensor types that took place between the submission of the FU3101 application and the project kick-off had the effect of calling the initial assessment of the way forward with respect to fibre optic sensors into question.

It was decided, that the specific tasks and milestones of the work package should be reconsidered in view of developments since the application was submitted: The price of certain very relevant types of fibre optic sensors has fallen drastically and some novel processing schemes had appeared.

The tasks WP2.1 and WP2.2 would be completed in full. But as there was seen to be no market in further developing these sensors for application in operating wind turbine blades, the investigation into the effect of the sensor on the bondline characteristics (task WP2.3) was not completed, and the improvement of the sensor design with respect to cost, production, implementation, response, etc. (task WP2.4) was only briefly addressed.

In this way, some activity in Work Package 2 was diverted into a re-assessment of the use of fibre optic sensors in wind turbine blades. In addition, the possibility of using wireless sensor systems (not fibre optic) relevant to remote condition monitoring of wind turbine blades was investigated, with this point linking especially to work being carried out in task WP3.2.

Practical work and results

The results of the prototype microbend transducer response to mechanical testing in the laboratory are described in a report [8] that fully covers the sub-tasks described in WP2.1 and WP2.2, but only partially addresses sub-tasks WP2.3 and WP2.4.

Test specimen preparation

The laboratory test specimen preparation involved gluing two composite pieces together with an adhesive thickness of 5mm, which was obtained using aluminium "spacers" between the two pieces. The microbend transducer was embedded within this glue-line with the fibre optic entering and leaving the adhesive protected by a silicon hose, see figure 5.

Figure 5. Showing the insertion of a fibre optic microbend transducer into the adhesive bondline during composite DCB specimen fabrication

It was also necessary to wrap the transducer in adhesive tape to protect it from the (initially liquid) adhesive and ensure it was free to move and affect the fibre optic when the test specimen was subjected to crack propagation in the bond line. The entire assembly process was very involved and in its' final form included spacers, use of adhesive tape, staged liquid adhesive application, clamping, pre-tensioning of the transducers and slip foil insertion to initiate crack growth. Ten specimens were manufactured in this way.

Crack propagation tests

The primary objective of these laboratory tests was to investigate the effect of shear stress in the adhesive layer on the crack-detection performance of the transducer. Also of great interest was the effectiveness of the transducer in maintaining contact with the composite pieces during crack propagation. The DCB test machine used for these tests was identical to that described in the Work Package 1 section of this report.

In every test case, the transmittance returned by the embedded microbend fibre optic was reduced as the crack propagated past the transducer. However, also in every case, the transmittance "recovered" after the crack had passed due to the fact that the transducer lost contact with one of the two composite pieces. See figure 6 for a typical example of the signal returned during such a test.

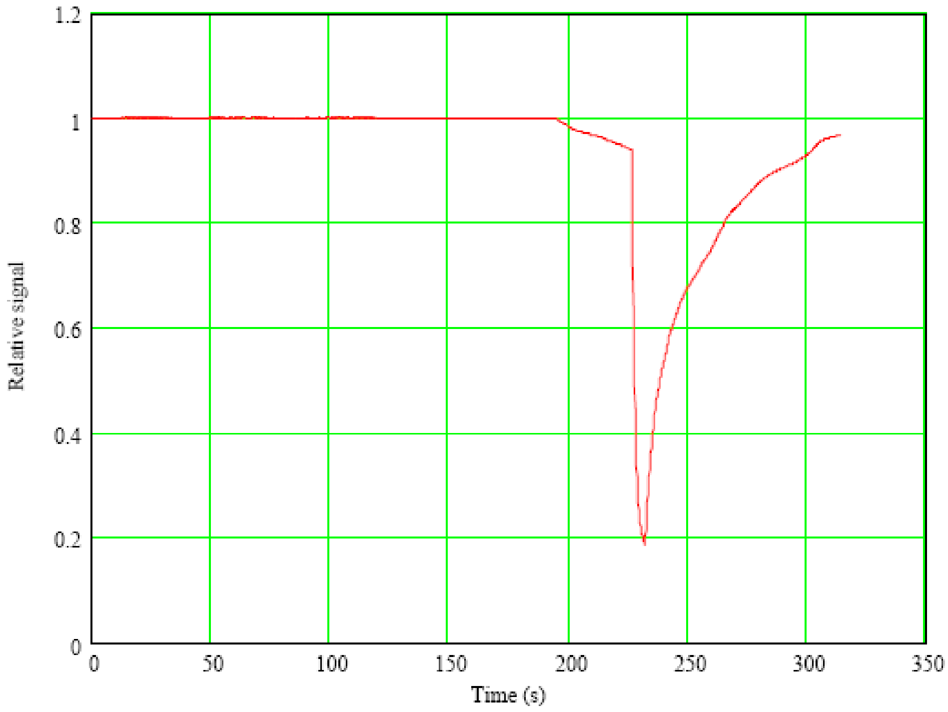


Figure 6. Signal response from the microbend transducer due to crack propagation.

Even under loading conditions as close to Mode I crack growth as possible, the thick adhesive layer proved highly likely to debond at the interface between the composite and the glue; and under mixed mode loading this was always the case. The tests showed therefore, that even though the deformation involved shear stress and the crack was progressed in the interface between the adhesive and fiber composite, it was still possible to the use the transducer signal as a clear indicator of the formation of a crack. The presence of the transducer itself in the adhesive bondline was also noted to affect the crack propagation and push the crack towards the interface (task WP2.3).

Sensitivity test

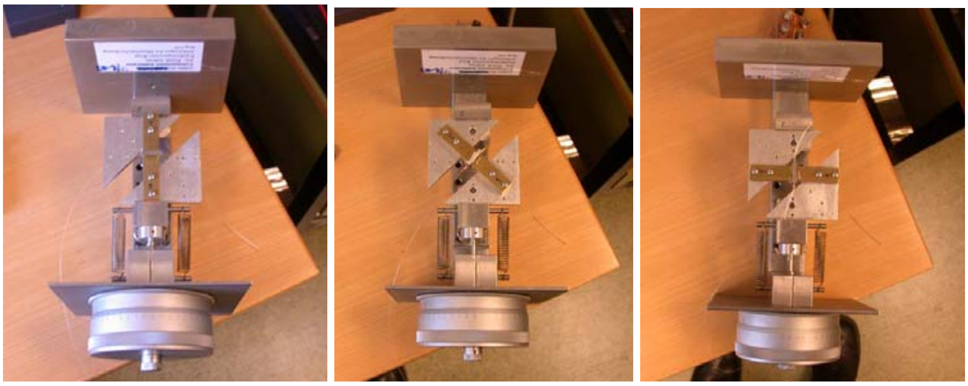


Figure 7. Showing the microbend transducer sensitivity being tested at 0, 45 and 90 degree angles

In order to test the transducer sensitivity, one was glued to brass handles that could be mounted in an extensometer calibrator in three different ways, as shown in figure 7. Rotating the large wheel of the extensometer calibrator translated the aluminium triangle closest to the wheel in a direction parallel to the rotational axis of the wheel. The displacement was read at the scale on the wheel. These tests were successful in demonstrating that the transducer, in this construction form, is absolutely insensitive to pure ‘shear-deformation’. However, a hysteresis effect was uncovered in cases where a permanent displacement of the transducer parts has taken place.

Reassessment of sensor approach

As part of the re-investigation of approach with respect to fibre optic sensor systems, the use of Fibre Bragg gratings, Fabry-Perot inferrometers, and new low-price interrogation units was proposed. Furthermore, various multiplexing schemes based on either wavelength division multiplexing (WDM), time division multiplexing (TDM), or hybrid multiplexing systems were considered. The purpose of multiplexing is to use a minimum number of fibres to fully instrument a large wind turbine blade structure. The issue of embedding fibre optic sensors was also a factor as the effect of the large (20 x 10 x 5 mm) mircobend transducer inside the adhesive bondline was a significant area of concern that could be avoided by using a fibre sensor (~200 um) such as the Bragg grating.

Various wireless sensor strategies (“stand alone” units that require neither cabling nor batteries) that are relevant for use in remote monitoring of wind turbine blades were identified as part of the re-prioritised Work Package 2. Parameters such as strain, temperature, acceleration, and moisture content can be measured with such systems and it is proposed that the issue of limited transmission range from such RFID (Radio Frequency Identification) transponders could be overcome by adapting the blade lightning conductor to act as an antenna, thus giving good coverage of the structure.

Piezoelectric sensors based on surface acoustic waves (SAW) were also considered worthy of further investigation, although currently still expensive in small production series.

Conclusion and future perspectives

The performance of the microbend transducer fibre optic sensor in laboratory testing has been investigated and verified. Other options for relevant sensors (both fibre optic and not) and wireless “passive” sensing approaches have also been considered for future application.

Results from the laboratory tests

The fibre optic microbend transducer successfully detected cracks growing in the adhesive bondline, when they pass the transducer; the cracks resulted in a reduction of the transmittance varying between 5% and 80%. In all tests the transducer lost contact to at least one of the fibre composite parts, and its transmittance resumed the initial value.

Although the quantitative value of the sensitivity tests is limited, it was concluded that the transducer is not sensitive to shear-deformation, but that mechanical displacement of transducer parts is possible and can result in a hysteresis effect.

Improvements suggested for the transducer after laboratory testing

When the transducer is mounted by simply inserting it into the adhesive layer between two layers of composite material, without any special mounting, it will not be able to detect cracks running in the composite material itself. Furthermore, it risks loosing its contact to the composite material as the laboratory tests showed. One idea to overcome these limitations is to mount the transducer with screws through the fibre composite into threads in the transducer. One screw from each side would be adequate to obtain a firm and durable connection between the transducer and the outer surfaces of the fibre composite plates. In this way it is anticipated that all cracks passing the transducer will be detectable, including those running within the composite material.

Future perspective for the microbend transducer

Due to the reduction in price for other approaches using fibre optic sensors, it was not considered economical to press onwards with the proposed design modifications for the microbend transducer, despite the crack detection properties of the sensor being promising and highly relevant for remote monitoring of wind turbine blades. Other fibre optic sensors are considered more attractive for development and implementation at this time as they are dropping in price, are based on already established hardware, and are simpler to embed in the composite laminate structure without adversely affecting properties.

Future perspectives following reassessment of other sensor types

Based on the investigations undertaken in this Work Package, it is suggested that the currently available wireless sensor technologies relevant for use on wind turbine blades would require either the use of an antenna built into the blade (a suggestion has been made to modify the lightning conductor for this purpose), or the use of batteries to transmit signals. A “wireless” sensor that included a local power source could achieve an unattended lifetime of at least five years. Energy harvesting technologies should also be considered [24] to allow such approaches to gather ambient energy from the structure for completing data processing and transmission throughout the lifetime of the wind turbine blade without the need for batteries.

Work Package 3

Developing damage detection techniques using inertia sensors

This section reports work performed in Work Package 3 of the PSO-F&U project entitled “Fundamentals for remote condition monitoring of wind turbine blades (Phase II)”, which is a successor of a related task in the project “Fundamentals for remote condition monitoring of wind turbine blades (Phase I)" that was successfully concluded in 2002; c.f. Larsen et al. [25].

The phase I investigations were restricted to *non-rotating* wind turbine blades. The *overall goal* of Work Package 3 in phase II is to mature the ideas defined in the initial project concerning the modal analysis approach to condition monitoring of operating wind turbines, or more specifically, to establish the fundamental knowledge necessary for the use of inertia sensors in a structural health monitoring system for *rotating* wind turbine blades.

Modal characteristics of dynamic structures change as a result of structural failures. This is caused by a derived change in stiffness (and damping) properties. The modal characteristics can be determined using a system identification approach, in which only the dynamic *response* of the actual structure to some unknown loading is utilized. Such an approach is ideally suited for wind turbine applications because the stochastic nature of the loading of such structures prevents detailed knowledge of the loading process to be obtained in any case.

The *basic idea* behind the WP3 approach is to compare reference modal characteristics, associated with the un-damaged blade, with continuously on-line recorded modal characteristics of the operating wind turbine blade. Identification of differences in such modal characteristics indicates a structural damage that potentially can be both localized and quantified by the developed methodology.

Objectives

In order to comply with the goal put forward, Work Package 3 was split into five subtasks of which the first is the most prominent and constitutes the basis for the remaining four. The original definition of the subtask contents is briefly described in the following.

- WP3.1

The possibility for tailoring the methodology applied in the pre-project to the loading conditions of a wind turbine blade will be investigated. More specifically the combined nature of the loading as composed of a periodic deterministic contribution (caused by the tower shadow and the mean wind shear) and a stochastic component (caused by the turbulence) will be attempted integrated in the output-only modal methodology.

- WP3.2

The potential of various inertia sensors (MEMS, wire less), as well as other types of sensors will be investigated with respect to their possible applicability with the present modal characteristics approach.

- WP3.3

The primary damage location aims at identifying the damaged blade cross section. However, in addition the possibilities for identifying the damage location more specifically in the damaged cross section is of interest as the "circumferical" position might indicate type of damage/fracture.

- WP3.4

In the Phase I project only mode shapes and frequencies were used for damage identification. The possibilities for extraction of supplementing relevant information for the damage diagnosis utilizing modal damping characteristics will be exploited.

- WP3.5

The price of a remote sensing system depends on the number of sensors, and investigations to minimize the number of sensors and optimize their positions on the blade will be performed.

Challenges

In the phase I project we used the commercially available output-only analysis software “ARTEMIS light” as the system identification approach to extract required information on modal characteristics from the response of a *non-rotating* wind turbine. Whereas the Work Package 3 formulation describes an effort in tailoring the output-only analysis methodology to the kind of *loading conditions* representative for a rotating wind turbine blade, the real challenge, in a system identification context, turned out to be related to the *system characteristics* of a rotating blade.

Conventional system identification tools (including the output-only modal analysis) rely on the two basic assumptions:

- The physical system can be described (or reasonably approximated) by a *linear* differential equation system; and
- The considered physical system is *time-invariant*.

For the rotating wind turbine blade structure, the first assumption is in general easily meet. The second assumption, however, is not satisfied, as the governing equation of motions will have *periodic (and thus time-dependent) coefficients*. This is the reason for the major complications introduced for performing a system identification of the rotating blade structure compared to the non-rotating blade structure.

This finding has significantly changed the starting point and thus the focus for the Work Package 3 activities, and most of the effort in Work Package 3 has consequently been devoted to the development of suitable system identification tools being able to deal with periodic systems. This change in the priorities has been necessary, because identification of the modal characteristics is the turning point of the modal approach and as such constitutes the basis for the other originally defined activities. As a derived consequence, the selection of suitable sensors and their optimal localization is hardly treated.

Models and results

System identification operates with three categories of modal structures – *white box models* that fully rely on knowledge to the physics of the system in focus; *grey box models* that only partly rely on knowledge to the physics of the system in focus; and *black box models* in which no physical knowledge to the dynamic system has been taken into account “a priory”. In the present context we have exploited the grey box- as well as the black box approach, respectively. The reason for taking a two-track approach was caused by difficulties with an “a priory” assessment of the likelihood of success or failure of the selected approaches – and thus linked to the basic nature of research! An extensive accounting of the derived algorithms can be found in Larsen and Hansen [9]. In the following, a summary of methods, results and perspectives are given.

Grey box approach

The basic philosophy of a grey box approach is to establish a mathematical description of the system in question, based on of the underlying physical laws, and then subsequently to derive missing input/output relations and/or model parameters by “calibrating” the relevant model to experimental data. For the rotating wind turbine blade the established mathematical model is a simplified elastic code of the rotating blade, and the “calibration” of the system parameters inside the model is achieved by use of an Extended Kalman filter.

During the process towards providing the present results a generalized tool has been developed which makes it easy to derive and apply other models as the basis for the Extended Kalman filter. This tool has already proven to be efficient and it will in the future be applied to investigate alternative models which include more DOFs in the WT model, such as the tower top DOFs, the edgewise DOF, etc.

At present, two different models have been tested by use of the generalized tool. The first model was described in [9] and contained only the stiffness and the damping of the blade as unknown parameters which were to be calibrated by the Extended Kalman filter. That model turned out to be insufficient to respond to simulated acceleration input supplied by the aeroelastic code, HAWC2. What was missing in the first model turned out to be a representation of the aerodynamic loading, so in the second model, a loading model was included which was intended to describe the harmonic aerodynamic loading caused by the rotation of the rotor. Besides from the stiffness and damping parameters contained in the first model, the second model contains 13 more parameters which describe the loading model. The 13 parameters describe the harmonics from one to six times the rotation frequency of the rotor, two for each harmonic, plus a constant term. The work related to the second model is reported in [3].

The methodology has not yet been tested with real data from measured observations. This will be the ultimate test of the methodology and is the final step in the plans for future work. But before that, the methodology is planned to be tested with simulated observations provided by an aeroelastic code, both for healthy and damaged blades.

Although the principles demonstrated are directed towards condition monitoring of wind turbine blades, they might be equally applicable for identification of defects in other structural components of the wind turbine.

Black box approach

As noted a black box model requires a priory no basic physics information on the system in question. This type of system identification approach is thus solely based on knowledge of the system response, which for a mechanical system, may be in the form of deflections, velocities or accelerations.

The proposed black box model is derived from scratch, and is “designed” to handle arbitrary *linear* systems with time varying, though *periodic,* coefficients. The basic idea is to split the compound periodic system identification problem into a number of low dimensional *independent linear constant coefficient* system identification problems, and subsequently to glue these individual sub-problem solutions together to the global solution using a derived Floquet based decomposition scheme.

Whereas existing attempts to identity linear periodic systems traditionally are developed within a numerical linear algebra framework, the present approach is based on/origin from the combined framework of numerical linear algebra and the theory for linear periodic first order differential equation systems. This results in a very flexible method in the sense that it allows for virtually all traditionally system identification algorithms – linear or non-linear (i.e. algorithms based on iterative optimization schemes) – to be applied for the identification of the defined/derived sub-problems. Furthermore, the method allows all types of loading to be considered (i.e. deterministic, that might include a direct feed-through term, as well as stochastic).

The algorithm requires that the selected output variables are recorded at sample intervals that are a fractional part of the system period. If this is not the case, synthetic time series with this characteristic must be constructed by suitable interpolation in the available data material.

In the first version of the proposed method, the dimension of the observation vector was required to equal the system order applied in the underlying sub-system identification procedures. This restriction has, however, subsequently been removed during the continued development of the identification scheme after the conclusion of the phase II project.

Conclusion and future perspective

Basic requirements of a structural health monitoring system to be of practical relevance are that it is robust, reliable, relatively cheap and provides the required information. The modal analysis based approach to conditional monitoring is considered to meet these requirements and is therefore foreseen to have promising perspectives in condition monitoring of wind turbine blades. As a built-in feature, it should be mentioned that only "essential" damages will give rise to (significant) modifications of the mode shapes, and the method thus implicitly includes a "filter" omitting insignificant damages.

In order to identify structural characteristics of rotating wind turbine blades, it has been necessary to develop system identification approaches able to deal with linear periodic systems. A new class of *black box* system identification algorithms for linear periodic systems has been proposed that are numerically relatively handy. In addition, a *grey box* approach, combining a simplified elastic model of the rotating blade with an Extended Kalman filter, has been developed, and it has been demonstrated that the Extended Kalman filter can be used to estimate "transient" modal characteristics of a simulated, simplified wind turbine model during operation.

Although the focus in the Work Package 3 formulation clearly is on inertia sensors, the derived formalism is of a more general character that applies to other types of sensor signals also (e.g. strain signals, velocity signals or displacement signals).

The proposed approaches have not yet been tested against full scale data. However, such tests are planned within an ongoing project in the future – hopefully both involving synthetic blade response data and full scale blade response data.

Work Package 4

Developing an approach for assessing blades with damage

In an earlier EFP-project [26], a wind turbine blade was on-purpose tested to failure in three steps, so that failure was obtained at three different locations along the blade. The results showed that wind turbine blades can fail by a number of different failure modes at the structural level. The fractures were so complicated that no attempt was made to trace back the sequence of the damage evolution in that study. The important point is that wind turbine blades are made of several structural parts and can fail by a number of failure modes. Obviously, the details of damage evolution will differ from one blade design to another. Nevertheless, it is fair to assume, irrespective of different design details and the different manufacturing technologies used by different blade manufactures, that many failure modes can develop in any blade before it fractures completely (i.e., looses its load carrying capacity). Any electricity producer that owns wind turbine power plants should ensure that no blades fail. This requires the capability to detect all the possible types of damages and the knowledge needed to assess the criticality of each failure mode.

It is therefore of major importance to develop tools that can detect damage before it become critical to the wind turbine structure. However, it is also essential to have model tools that can assess the effect of a given type of damage on the residual strength and fatigue life of the wind turbine blade. This is complicated by the fact that many failure modes are possible. Consequently, many fracture models must be mastered and many fracture properties must be measured before this can be accomplished.

Objectives

The overall goal of this WP was to draw up an approach which allows *quantitatively evaluation* of the strength reduction of damaged area in a wind turbine, if it type of damage, it size and location is known. This requires knowledge about the stress state in the wind turbine blade, accounting for the specific type of damage, knowledge of the materials laws that control the damage evolution. Originally, a literature survey (models of fracture modes) was planned to be the major part; however a simple example was also planned for demonstration of the approach.

The work in WP4 was planned in three tasks:

- Task 4.1. Identification of central material parameters: For each failure mode it must be established which material laws control the damage evolution under static (ultimate load) and cyclic load (fatigue). Furthermore, it must be clarified how the relevant material properties are determined by laboratory tests.

- Task 4.2. Approach for analysis of a blade with damage: Modelling of a wind turbine blade, e.g. by the finite element method, is required for determining whether or not a given damage type can propagate. A coupling between a full 3D, but coarse, model and a finer, more detailed model should be considered. Directions will be sketched to when a damage is considered insignificant (false alarm), significant (requires a repair) and critical (blade must be replaced).

- Task 4.3 Demonstration of approach: A simple example was planned for the demonstration of the principle of the approach: First relevant material properties are measured. Next, a specimen having a given damage is modelled and the damage evolution is predicted. Finally, a specimen, having an artificial damage of the type analysed is made and tested. The damage evolution experienced is compared with the predicted damage evolution.

Milestone: A report describing the approach for the estimation of residual life

Progress/Changes during the project

Work was only done at the first two Tasks (4.1. and 4.2). During the project, a major part of the time that was originally allocated to this WP was re-allocated to WP5 - the full scale testing. Therefore, Task 4.3 was not initiated and therefore not met. A small report, covering Task 4.1 and a part of Task 4.2, was written [10].

Description of work

A literature survey was made, structural failure modes were categorised, and material properties that control static strength and failure under cyclic loading were listed. Test methods that are suitable for the determination of these material properties were reviewed. A few ideas for an approach combining structural health monitoring (SHM), non-destructive testing (NDT) and modelling of damaged wind turbine blades were outlined.

This report contains a literature survey containing 44 references to relevant work in the areas of material models and materials test methods. Of these references, nine are from 2003 (the year the project started) or newer.

Results

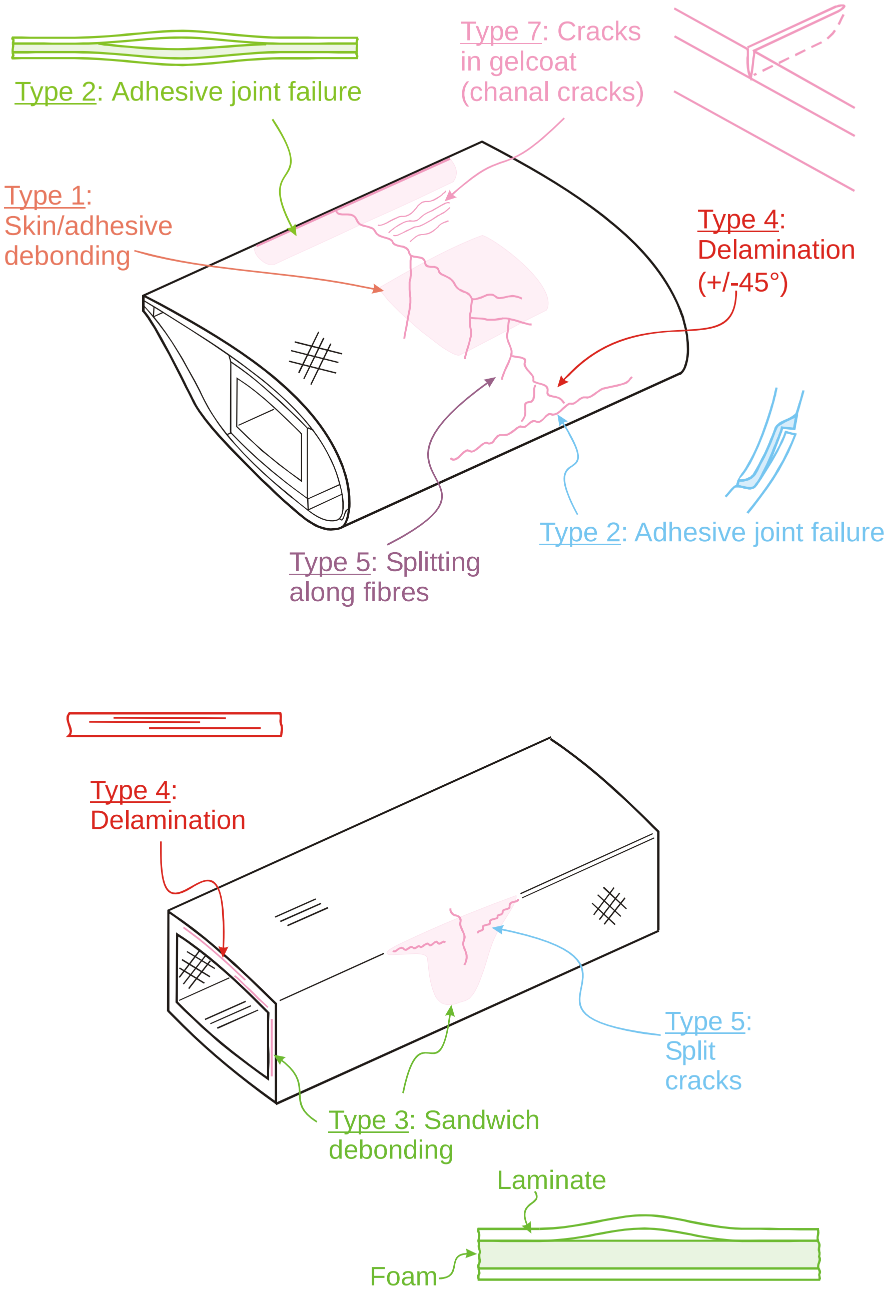
Starting from the overall level of a wind turbine blade, the structural failure modes were categorised in 5 types:

- Adhesive joint failure
- Sandwich structure failure
- Laminate failure
- Gelcoat/skin delamination
- Gelcoat cracking

These were furthermore subdivided into 14 basic damage modes. For each of these a relevant material property, controlling strength was defined. These are

- 4 strength values (tension, compression, shear)
- 7 fracture energy values
- 3 cohesive laws

Figure 8 shows some of the wide variation in structural failure and material damage modes possible in the wind turbine blade, illustrating the need to identify the key material properties that control the growth of the most critical damage types under different operational loading regimes.



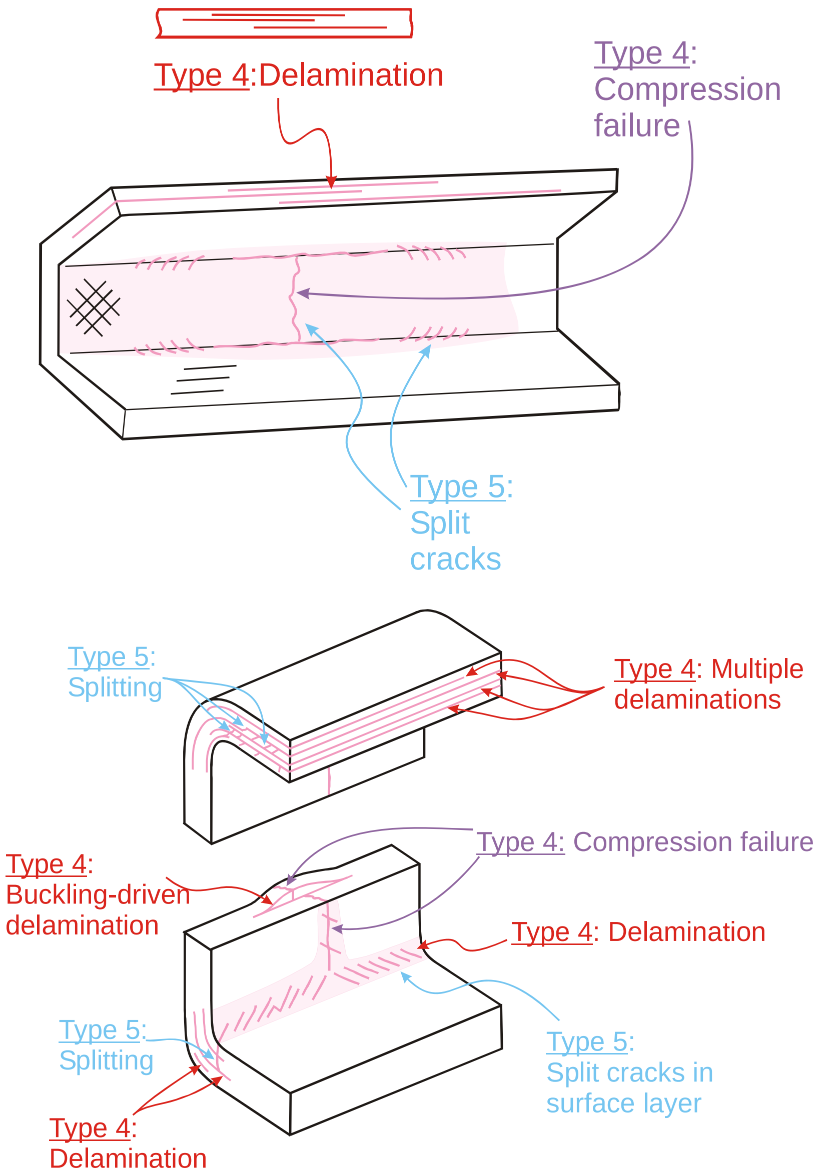


Figure 8. Sketches showing failure modes observed in a wind turbine blade subjected to full-scale testing [26]

Strength values represent the maximum stress that the material can carry under static monotonic loading. Fracture energy (sometimes called the critical energy release rate) represents the energy uptake of a crack tip during crack propagation. A cohesive law is the stress-opening response of a fracture process zone, i.e. the stress transmitted between the crack faces as a function of the crack opening. These different properties (strength values, fracture energies and cohesive laws) are used to describe different modes of damages: the formation of a damage zone, crack propagation and cracks experiencing large scale fibre bridging. Some of these fracture energies, e.g. interfacial fracture energies and cohesive laws, is actually not just a single property, but can depend on the combination of tangential to opening ratio of the displacements of the crack faces. For instance, the fracture energy can be measured as a function of the so-called mode mixity [27].

The strength of uncracked/unnotched structures decreases during cyclic loading; for parts that contain flaws or cracks, the cracks can grow in size during cyclic loading. The relevant material properties are:

- Relationship between number of cycles to failure and maximum cyclic stress (S-N data)
- Crack growth rates (Paris-Erdogan law)

Materials experiencing large scale bridging under cyclic crack growth should be characterised by cyclic cohesive laws. These are likely to be different from those of monotonic crack opening. This topic has not been sufficiently addressed in the published literature.

The report [10] also covers an overview of relevant test methods for the determination of the strength, fracture energy and cohesive laws. The test methods are only briefly described, no details are given about the specimen geometry and test methodology; instead appropriate references are given to the published literature. The test methods include 5 test methods for tension, compression and shear strength and 9 fracture mechanics test methods for measurement of fracture energy. Some, but not all, of the fracture mechanics test methods are suitable for determination of cohesive laws using a J integral approach. References are given to 9 relevant ISO and ASTM standards for testing methods.

A brief outline is given to an approach for the avoidance of failure of wind turbine blades. This involves combination of experimental methods for the determination of relevant fracture properties, SHM for the detection of damage evolution, NDT inspections for the accurate determination of crack position, the crack size and crack shape and modelling of the blade with the detected damage. The modelling can be done, e.g. using numerical models such as the Finite Element Method. In such models, stress based criteria can easily be used. Furthermore, cracks can be modelled and the energy release rate can be calculated along the crack front. Predictions for crack growth rate can then be made using the Paris-Erdogan law. Prediction of the residual life (the number of load cyclic before the crack propagates rapidly) can be made by modelling cracks with different crack length; rapid crack growth can occur when the energy release rate attains a critical value corresponding to the fracture energy. Models using cohesive laws are emerging.

Discussions and perspectives

The work done in WP4 was not as much as originally planned. Milestones were only partially met.

Never the less, on the basis of the literature study, it seems possible, with the existing knowledge, experimental methods and modelling technique, to construct a fairly rough finite element model that includes a crack, for instance a delamination, and predict the onset of cracking using fracture energy as a criterion. Advanced modelling approaches, such as local remeshing or multiscale modelling, may be useful. However, it is more challenging to predict crack growth using cohesive zone modelling. However, much more work is needed to demonstrate that the modelling is robust (i.e. numerical stable) and that predictions are accurate and reliable. This should be done by comparing strength predictions, made using strength properties obtained from laboratory test specimens, with experimental results (strength measurements) of structures, preferably of another size and geometry than the test specimens.

Another area that requires a lot more attention is cyclic crack growth under large scale bridging. Knowledge is lacking, both in characterisation and modelling. These issues should be addressed in the future.

Work Package 5

Applying AE in a full scale fatigue test to blade failure

This section reports the work performed in Work Package 5 (WP5) of the PSO-F&U project entitled "Fundamentals for remote condition monitoring of wind turbine blades (Phase II)" describing the application of sensor and inspection technology on a wind turbine blade undergoing testing.

Previous project work of this kind undertaken during the pre-project [17] had focussed on using the sensors and inspection systems to detect different damage types grown under specially applied static load conditions. The overall goal of WP5 is to document a blade test to failure under fatigue loading where the information obtained via the use of mounted sensors and NDT inspections allows a perspective on the initiation of damage, its development under cyclic loading, and the ultimate failure of the material and structure.

Therefore, in this test configuration there would be no initiated damage which a controlled application of load would develop in a predictable way. Instead the structure would be subjected to dynamic loading and the initiation and growth of damage would be more uncertain, both in terms of when in the test series and where in the blade structure the damage might initiate, and in terms of the combination of different material failure types that would occur from which a critical type would develop into fracture of the blade structure. In other words, this structure test (although not "realistic" as such) more closely corresponds to operating loading conditions and is very similar to standard fatigue test configurations regularly undertaken by commercial blade test facilities.

Subtasks in Work Package 5

To achieve this perspective the following sub-tasks were proposed.

- WP5.1

Planning of the test involves agreement with all partners concerning the type and orientation of loading, the measurement approach with respect to load application and the positioning of the load(s). The extra sensor measurements and NDT inspections must also be determined and incorporated into an agreed test schedule covering several months.

- WP5.2

Pre-inspection of the test blade is a necessity to determine the distribution of defect/damage condition already present. This requires full visual inspection as well as scheduling ultrasonic and x-ray inspections of the most significant structural locations.

- WP5.3

Instrumentation and calibration of the blade with sensors (displacement transducers, traditional resistance strain gauges and acoustic emission).

- WP5.4

Test of the blade to structural failure. Cyclic loading of the blade at progressively higher load levels in order to quickly generate damage that can be detected by the mounted sensors. The localisation of damage by the sensors will provoke a halt in the testing to allow NDT inspections to take place. Fatigue loading will then continue to develop the damage further (and possibly allow subsequent inspections) and ultimately provoke visual structural failure.

- WP5.5

Post test analysis of the destroyed blade. All damage types to be identified and categorised.

- WP5.6

Data analysis and reporting of the test to combine all available measurements, and the input from the pre and post failure inspections.

Challenges encountered during the testing

The completion of any full scale structural test involving continuous monitoring requires a significant mobilisation of manpower and facility resources and a good co-ordination of all involved partners; particularly where that monitoring data can provoke an inspection period at short warning.

For this Work Package the end user partner in the consortium (Bonus Energy /Siemens Energy) made the major commitment of providing a test blade (B40) and a facility for fatigue testing this blade to failure. During the testing the consortium would have full control of the process, allowing the time for extra sensor application on the blade and unconventional NDT inspections as part of the research effort, and specifying the loading conditions and necessary in-test inspection periods in order to meet the objectives of the Work Package.

Following detailed discussion between all partners, and visits to inspect the blade and test facility, a plan was proposed and agreed by the consortium. The blade was to be tested in edge-wise fatigue at high dynamic loads in order to provoke a rapid initiation and development of damage to a structural failure in the blade within a few weeks of testing. This was the most extreme fatigue load condition it was possible to create.

Once the loading plan was agreed the blade was mounted in the test fixture and prepared with the rotating mass load applicator and balancing weight attachments necessary to stimulate the dynamic loads specified. A full visual inspection was conducted on the entire blade, and specialised x-ray and Ultrasonic inspections were carried out on the specific structural location where damage development was anticipated. These inspections were required to provide information about the “pre-test” condition of the blade.

A zonal AE instrumentation plan was implemented that would provide maximum structural coverage with the available hardware. This system would continuously monitor stress wave activity distribution within the structure for the duration of the fatigue testing. Significant changes in the data would provoke a pause in the test in order to conduct inspections (visual and eventually NDT) at the structural locations indicated.

At this point the blade was ready to begin testing and the activities specified in tasks WP5.1, WP5.2 and WP5.3 had been completed in full. The Project had started on April 2003 and testing of the B40 blade began in September 2004. Unfortunately it was necessary to halt the fatigue testing of the blade almost immediately after it had begun when it was discovered that the foundation of the test rig had become damaged and was no longer stable under the dynamic loading of the test. It was likely that the high loads associated with this test had themselves caused the damage to the test stand foundation. Due to the age of the test fixture it was not economic to repair it and the test as planned by the consortium was therefore abandoned.

Although only a very limited amount fatigue loading had been imparted to the blade, and no useful data had been recorded by the AE monitoring system, it was decided to conduct the follow up inspections by x-ray and Ultrasonic equipment as planned in the Work Package 5 description. These inspections confirmed that no damage had in fact been initiated in the B40 blade.

This serious set-back required a reassessment of what it was now possible to achieve in Work Package 5. All the planning and set-up has been conducted, including the instrumentation and pre- and post-inspection effort without receiving any reward in terms of data. The blade was still available but it was no longer possible to test it as the initial test stand was now destroyed and there was no spare capacity where the blade could be tested elsewhere

In order to generate some data for WP5 (sensor monitoring and NDT inspection) the consortium agreed to attend to a standard certification test on a different blade (B45) scheduled for static and fatigue loading on a newly constructed test fixture. In this second attempt, the consortium would be given access to a test being conducted on a blade undergoing certification testing. This would involve an initial static test loading of the blade to operational levels, followed by a fatigue series simulating a standard life-time load condition.

An important difference in this “back-up” scenario was that there was no expectation of any damage development in the B45 blade, either under the initial static loading, or during the fatigue loading. Furthermore the commercial pressures, associated with all standard certification testing, meant that although the consortium expressed interest in performing additional post test static loadings and a subsequent fatigue load at higher levels, this could not be guaranteed.

After the initial static loads (described below) a standard fatigue sequence was initiated lasting for six months. At the end of this period it was hoped that the blade could remain in the test fixture and re-configured in order to perform a series of static loads similar to those undertaken at the start of the test period, followed by a high loading fatigue sequence intended to promote the rapid initiation and growth of damage in the blade. However, due to extreme pressure on the new test facility to complete commercial certification of other blades, this research work was not completed. After standard testing the B45 blade was immediately removed from the test stand; whereupon it was made available for post test NDT inspections.

Test and inspection results

The test report generated in Work Package 5 [11] tells the story of the failed attempt to apply high fatigue loading to structural failure on the initial project blade (B40). It also documents the initial series of static load testing conducted on the standard certification blade (B45) with AE sensor monitoring. The NDT inspections of B40 and B45 blades are included for both ultrasonic and x-ray techniques. The development of these inspection techniques using representative sections of material taken over the course of the project is also described. This is an internal report containing information classed as “commercial-in-confidence”.

For the B40 fatigue test, a 16 channel SIMPAL AE system from Holroyd Instruments in the UK was used. This system consists of a central controller module and two measurement nodes with eight available sensor channels in each. The sensors used were low profile AESS1 and a GSM modem was used with the system to allow a regular remote download of the recorded AE data.

The AE sensors were attached to the blade with epoxy adhesive whilst it was mounted in the test rig. Cabling from the sensors was brought together into an umbilicus and anchored along the blade length into the control module where the SIMPAL system was linked to a mobile phone SIM card and antenna.

From the first measurement module, seven sensors were placed around the blade diameter at chord 3m. During the planned lateral fatigue loading this chord would be under the greatest strain and therefore of most interest for the monitoring. The eighth sensor from this module was designated an “environmental” sensor and it was placed against an unloaded structure (the control module), its’ activity profile was assigned to environmental effects such as wind and rain. The eight sensors from the second measurement module were placed in matched pairs (trailing edge and leading edge) at 6m, 9m, 12m and 15m blade chords in order to provide a profile of the stress wave activity along the length of the blade as it underwent fatigue loading.

As no significant testing of this blade took place there was no relevant data obtained by the AE monitoring, and no damage was detected by the pre- and post-test NDT inspections.

For the testing of B45, a similar AE sensor scheme was chosen whereby the blade chord at 6m was monitored by a ring of sensors, and matching pairs of sensors (leading edge and suction face) were positioned at 8m, 10m, 12m and 14m chord lengths. For this test the B45 blade would be loaded vertically (with the use of a crane) from one of five loading yokes mounted at blade chords 27m, 31m, 35m, 39m and 43m. The new test stand made it possible to rotate the blade and thus load in four different orientations (pressure side up, suction side up, leading edge up, and trailing edge up).

Each of the static loadings were conducted in a step-wise manner; a test factor corresponding to 40%, 70%, 100%, 135% and 149% of the maximum expected in-service loading was calculated in tonnes of applied load for each of the blade orientation and loading position combinations. In each test the static load applied was increased to the next test factor and held until the resulting AE activity died down, and then the load was increased once more until the next test factor load was achieved. After the load hold at 149% of the maximum expected in-service, the applied load was reduced to zero again in a controlled way. This created a series of Acoustic Emission profiles for the blade structure under various loading orientations and severities, with the different sensors responding to the stresses generated at that location in the blade.

There follows a summary of some of the specific information provided by the AE monitoring of this structure test.

All the activity detected by the AE monitoring was associated with the load application. On each occasion, the activity during load increase died down rapidly in the load hold period indicating that the blade can safely maintain the applied static load. Any continuing AE activity during a load hold would indicate (and localise) the presence of a growing damage/defect in the structure.

The particular AE sensors showing activity during each load application depended upon the orientation of the blade, suggesting that an operating environment response can be mapped using sensor output.

In most cases where AE activity is being detected there is no audible sound from the tested structure. However on some occasions, especially during the high level loading, there was structural cracking and crunching sounds heard from the blade. While it is impossible to distinguish where in the blade structure such noise is coming from using the human ear, it is a simple matter to confirm where the corresponding burst of AE activity was centred using this monitoring system.

During this series of static tests, a profile of AE activity along the length of the blade was generated for each load orientation. Subsequent loadings of a given type (orientation and load position) will generate similar profiles of activity, with any changes suggesting the presence of damage.

Conclusion and future perspective

A full scale turbine blade test has been conducted with real time monitoring from Acoustic Emission sensors. 18 different loading configurations of load location and blade orientation were undertaken and the different AE profiles for each configuration compared. Each load consisted of a stepwise increase in applied stress up to 150% of design load expected. Inspections using ultrasonic and x-ray techniques have been conducted to search for any subsequent damage development.

Experience has been gained, for both the sensor supplier and the blade manufacturer, in the practical application of the AE monitoring technique in such a way as to give a valuable “activity profile” during the course of the testing. New insights have been reached as to the ways in which future testing (both specialised and standard) can benefit from new AE measurement possibilities. Furthermore, possible options for in-situ measurements for working turbine blades have been raised. The optimised use of modified inspection techniques, based on ultrasonic and x-ray, was successfully investigated during the blade testing.

One key conclusion from the activities in Work Package 5 was that commercial test facilities will always be under strong pressure to carry out vital certification testing for blades involving approved standard load applications. This naturally limits the options for trialling non-standard load types, monitoring systems, and NDT applications where commercial pressures act on the time and effort that can be added to what are already expensive test procedures.

The experiences in this project and others have convinced Risø DTU that it is necessary to invest in research focussed test facilities capable of providing a multi-scale approach to material and structural response, damage identification and progression, monitoring and inspection technologies, and so on. Work is in progress to establish versatile sub-component and full-scale test facilities for wind energy (and other industrial) structures that will provide a unique research environment for deepening the understanding of composite material failure mode interactions from nano/microscale to the structural level (and similar problems in other structural materials). Such a facility will also support hybrid testing, where the test output from monitored sub-components interact in real-time with a computer simulation of the full structure, thus establishing intelligent boundary conditions for the tested component. The multifunctional aspect of the testing reflects the fact that industry is generally moving towards integrating and optimising several functions in the same structural component. The possibilities for advancing SHM technology using such an experimental facility are obvious.

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